Reservoir Monitoring Consortium (RMC)

Annual Project Review Meeting

CO_2 EOR Reservoir Workflow

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CO_2 EOR

- Considered the ‘best’ choice of EOR (vs. Chemical methods) for High Temperature & Salinity Carbonates
  - High Reservoir Pressure
  - Favorable Mobility
  - Shortage of HC gas for miscible injection
  - Issues with N2 Injection (high Miscibility pressures, cost and CO_2 emission)
- Main Considerations:
  - Availability & Cost
  - Vertical & Areal Sweep
  - Wells and Facilities
  - HSE

Middle East Applications

- Pilot Studies
- CO_2 EOR Reservoir Screening done by ADCO
- Rumaitha CO_2 EOR Pilot Results
- BAB CO_2 EOR Pilot
- Aramco CO_2 EOR Pilot
- In design stage for other reservoirs

Recent Publications

1) **Evaluation of the Efficient Displacement Pressure in a CO_2 Pilot Feasibility Study in a Giant Carbonate Oil Reservoir**, Cédric Clara, Ahmed Elsayed Ali, Ilhan Sener*, SPE, Abu Dhabi Company for Onshore Oil Operations (ADCO)

2) **Design and Implementation of the first CO_2-EOR Pilot in Abu Dhabi, UAE,** *Salma Al Hajeri, Shahin Negahban, Ghaniya Al-Yafei, Ali Al Basry, SPE, Abu Dhabi Company for Onshore Oil Operations (ADCO)*

3) **Lessons Learned from the First Miscible CO_2-EOR Pilot Project in Heterogeneous Carbonate Oil Reservoir in Abu Dhabi, UAE**, *A. Al Basry, S. Al Hajeri, H. Saadawi, F. Al Aryani, A. Obeidi, S. Negahban, G. Al Yafei, Abu Dhabi Company for Onshore Oil Operations (ADCO)*

4) **EOR Potential in the Middle East: Current and Future Trends,** Saad M. Al-Mutairi, SPE and Sunil L. Kokal, SPE, Saudi Aramco

Pilot Objectives

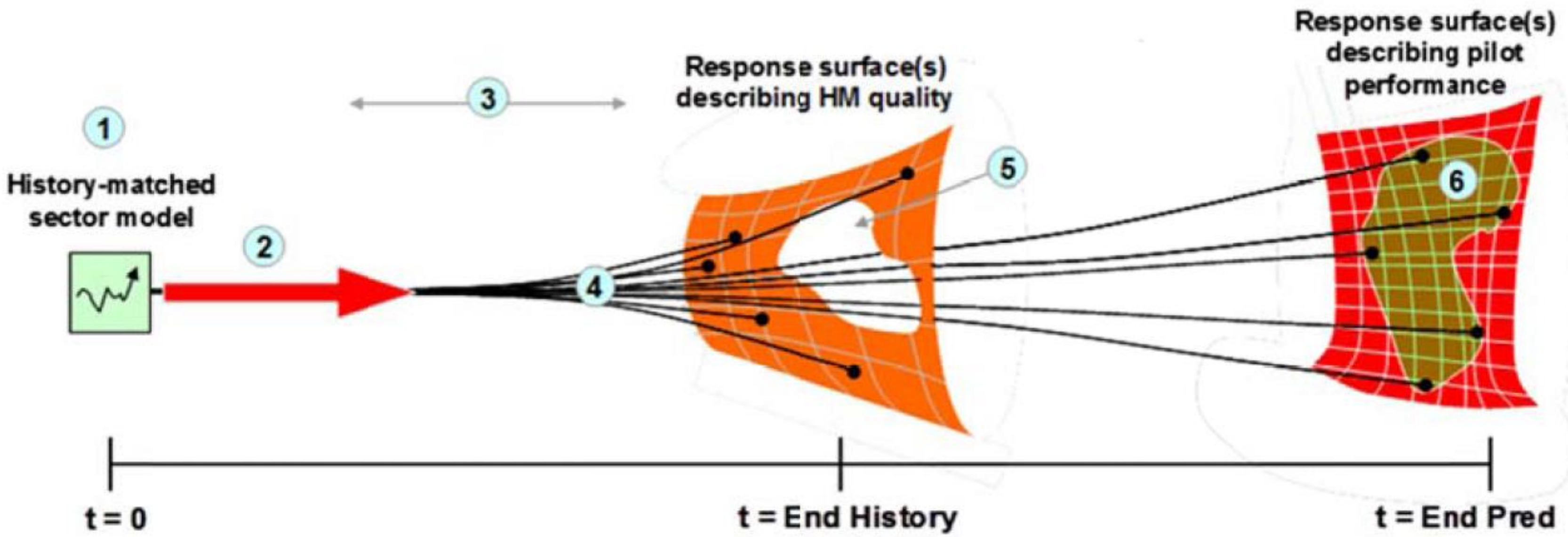
- Evaluate EOR Potential (Ultimate Recovery)
- Recovery of ‘Difficult Oil’ (low, heterogeneous permeability)
- Reduce the uncertainty with EOR Performance prediction (Production, Recovery)
- Efficient use of CO_2

Example of Evaluation Criteria*

Evaluation criterion	Description	Design consideration
Sweep efficiency	On a relative basis, how well is the pilot concept expected to improve sweep efficiency over the existing development plan?	EOR potential / difficult oil
Interpretability	Will results from the pilot concept be able to be interpreted?	EOR potential / performance prediction
Scalability	On a relative basis, how easy will it be to scale up the pilot concept (from a subsurface perspective) to full-field?	Future phasing
CO_2 containment	Will the pilot concept limit CO_2 movement out of pattern (horizontally and vertically)?	EOR potential / "do no harm" to existing facilities
Cost	On a relative basis, what investment in wells and completions is required to implement the pilot concept?	Future phasing
Operational complexity	On a relative basis, how difficult will it be to successfully execute and operate the pilot?	Execution
Flexibility	On a relative basis, how will operational problems impact the ability of the pilot to achieve its objectives?	EOR potential / execution / CO_2 utilization

* Ref 1. in Slide 4

Monte Carlo Simulations*



1 Define HM tolerances

2 Run simulations from t=0 through to end of prediction

3 Develop equations describing HM error and pilot performance responses

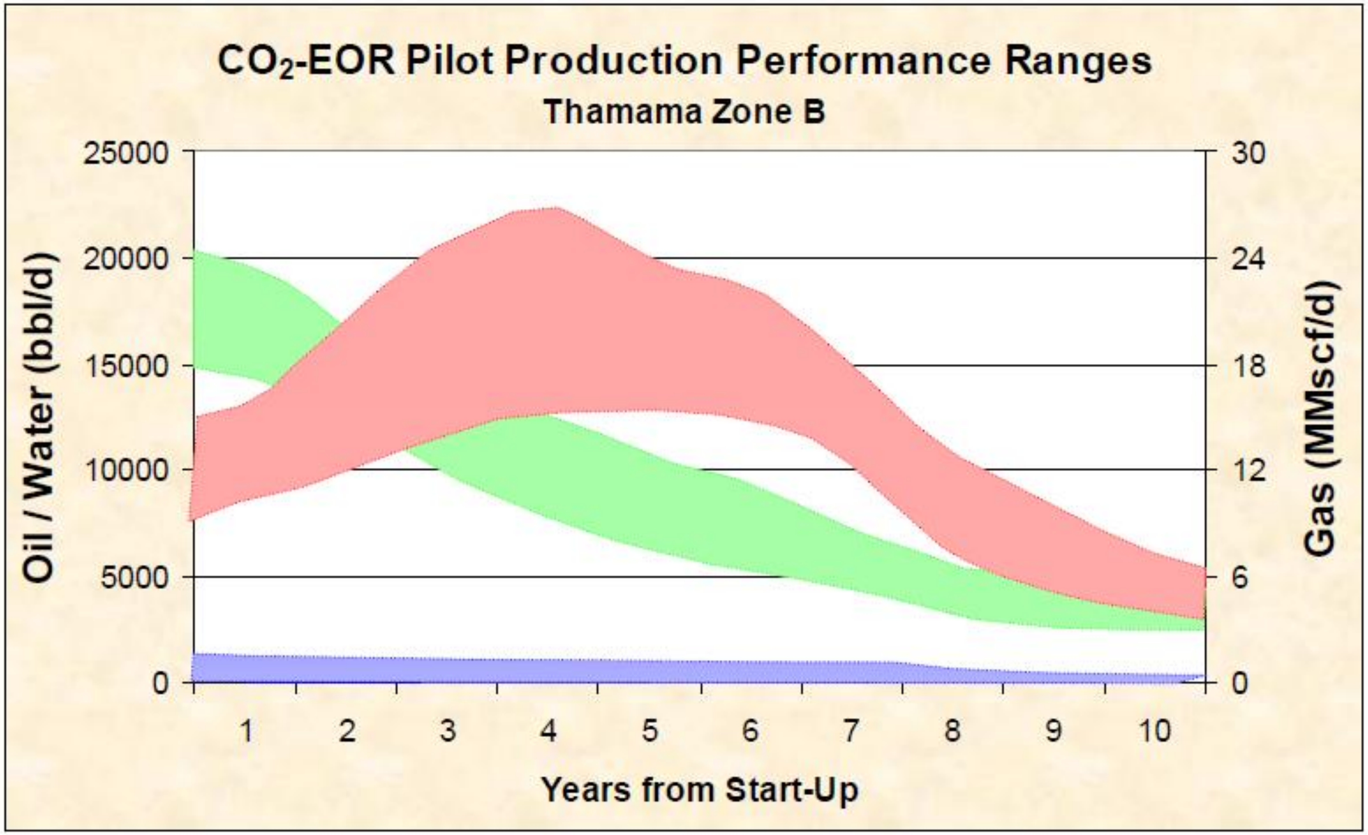
4 Run Monte Carlo simulations on the equations

5 Filter out MC simulations that do not meet HM error tolerances

6 Use surviving MC simulations to develop exceedence curves that quantify expected pilot performance range

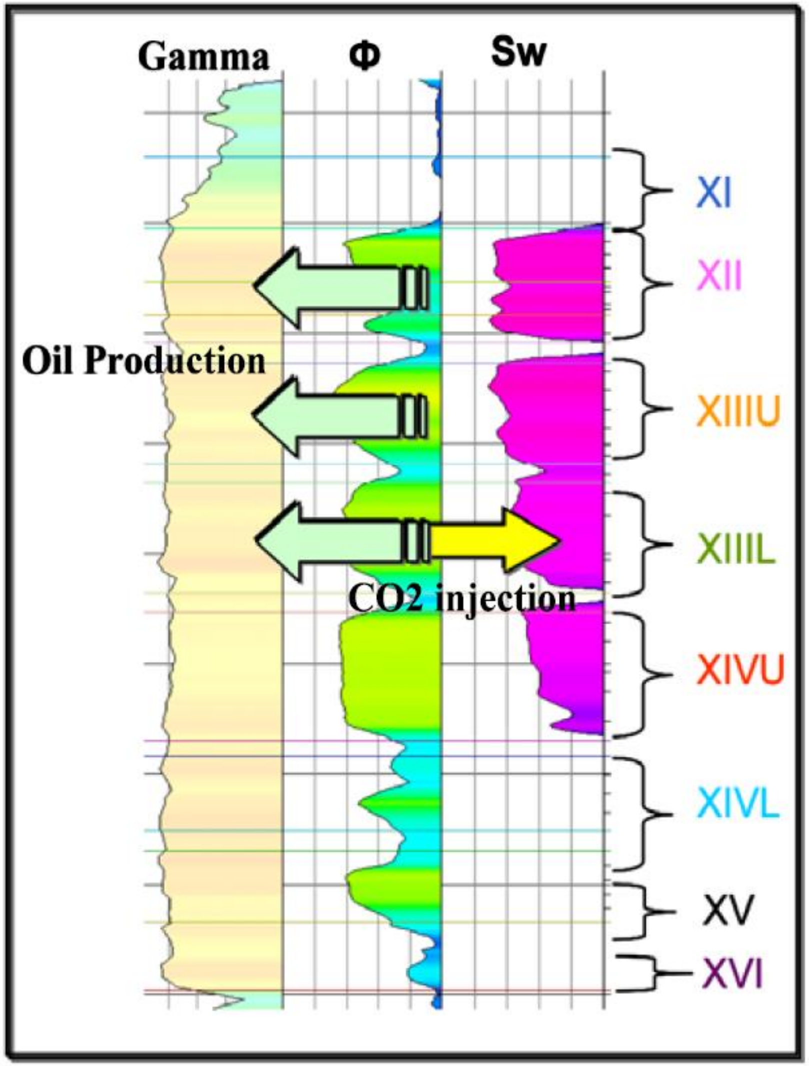
* Ref 1.

Pilot Production Performance Ranges*



*Ref 1

CO_2 Injection/Production Zones*



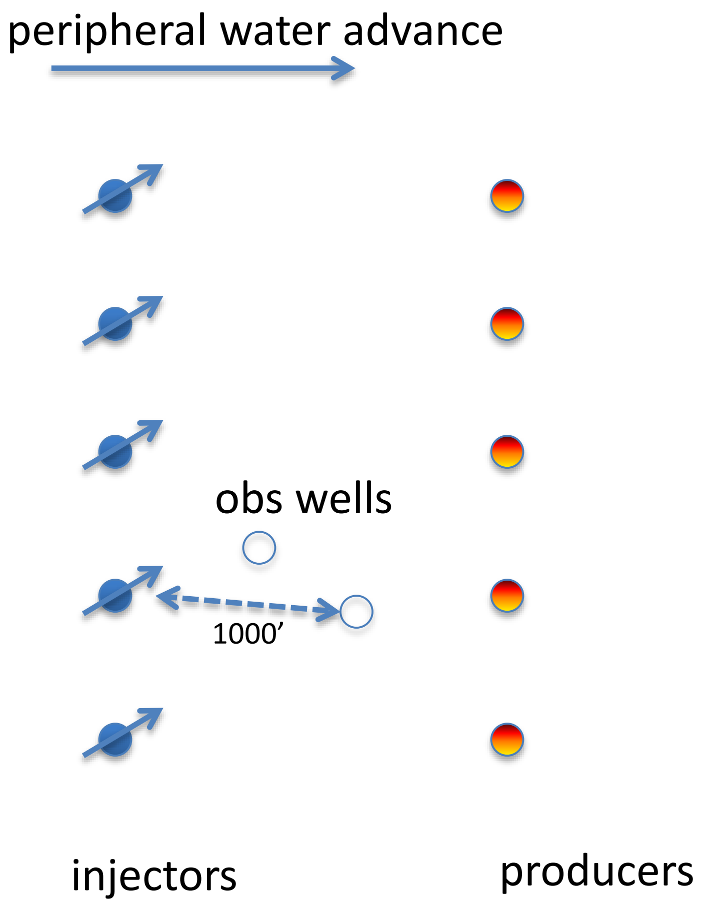
* Ref 2

Pilot Results*

- CO_2 breakthrough occurred faster than expected (based on surface metering with CO_2 analyzers).
- C/O Logging showed CO_2 advance within the high-perm streak in the reservoir.
  - High resolution simulations also confirmed the CO_2 breakthrough
- No main issues with injectivity, asphaltene deposition.
- Large negative skin in injector indicating possible induced fracture
- CO_2 jet impacted one of the tubulars at the producer.
- X-Well Seismic did not perform as expected.

* Ref 2

CO_2 Pilot - Giant MEA Reservoir



- Miscible Injection
- Line drive with vertical injectors and producers
- OH Observation Well(s)
- First inject water before CO_2 and determine Residual and Remaining Oil
- 6 months of CO_2 injection followed by 6 months of water injection
- Monitor Change in Oil Saturation after CO_2 flood
- Simulations show gravity override of injected CO_2 into top zones

Overall Assessment of the CO_2 Pilot

- \+ Appropriate well spacing inline with field implementation
- \+ Vertical wells for accurate reservoir description and control (as opposed to horizontal injectors / producers)
- \+ Continuous Seismic Monitoring as well as X-Well Seismic & EM measurements for Saturation Monitoring
- \- Passive Pilot without Control
  - \- No mechanical control in injectors and producers
  - \- No sandface pressure measurements
- \- OH Observation Wells could be problematic from the saturation monitoring point of view (crossflow of CO_2 between different reservoir zones)

Lessons Learned

- Pilot dimensions should be in line with key objectives of the pilot (neither too small nor too large)
- 'Active' Pilot instead of 'passive' information gathering
- Wells & Completions that are in line with field implementation
  - Mechanical Controls & Chemical Methods
- Need for Robust Measurements for Monitoring
  - Inter-Well (2D or 3D) Saturation measurements that can resolve various phases: Oil, Water and Miscible Agents (EM, Seismic, Gravity, Pressure, etc.)
  - Distributed Pressure / Temperature Measurements sensing the formation (rather than the wellbore)

Research Focus

- Reservoir Workflow: Data Integration and Fast Feedback loop for Optimum Displacement & Oil Recovery:
  - Incorporate both discrete and continuous measurements (Seismic, EM, Pressure…)
  - Reduce Uncertainty with multiple realizations
- Benefits:
  - Early detection of Reservoir Risks (gravity override, early breakthrough of injected agents, etc.)
  - Mitigation vis-à-vis Controls in-place (both mechanical & chemical methods)

Challenges

- Computation Time:
  - High Resolution Reservoir models (thief zones, fractures, flow barriers)
  - Large Number of Cases due to Uncertainty (vertical communication, reservoir contrasts, fracture corridors, etc.)
- Measurement Sensitivities:
  - Multi-Phase displacements: Supercritical CO_2, Water and Oil
- Inversion:
  - Deterministic approach: applicable to limited cases
  - Stochastic approach: Not very practical in many field applications
  - Heuristic Methods combining these two